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Subject: Application of Hall Plot Analysis for Formation Testing

Executive Summary

The Hall Plot and the Hall Slope use readily available operational data to analyze well injectivity. By plotting the Hall Integral and the Hall Slope against the cumulative injection volume, changes to the well injectivity can be used to indicate formation damage, identify fracturing, or evaluate stimulations. However, the Hall Plot only provides limited quantitative data regarding formation damage, fracturing, and stimulation. To quantify the changes to permeability and skin or to identify fracture length, a falloff test should be performed. To identify the fracture pressure, a step rate test should be performed.

Background

The Hall Plot, when used properly, is a useful tool for analyzing an injection well and the formation around it, but it does have many limitations. The primary function of the Hall Plot is to analyze the well injectivity. The injectivity is influenced by several factors like the well completion, formation skin, operational parameters, and other formation properties. This analysis is accomplished by graphing the cumulative pressure difference (the Hall Integral, H_i) against the cumulative injection volume (W_i). The slope of the plot is an indicator of the injectivity of the well. The Hall Plot analysis is specifically an effective tool for evaluating well treatments, as well treatments aim to modify the well injectivity. However, by plotting the derivative of the H_i (also referred to as the Hall Slope, m_H), in addition to the H_i itself, formation plugging and fracturing due to injection operations can be observed over time. Below, I will discuss what the Hall Plot analysis and derivative analysis is and how they are used.

Method

The Hall Plot is constructed using real-time production data: injection rate (Q_w), and bottomhole pressure (P_{wf}). The Hall Plot has the cumulative pressure difference (H_i) and the Hall Slope (m_H) on the Y-axis, and the cumulative injection volume (W_i) on the X-axis. H_i is calculated with Equation 1. W_i is calculated with Equation 2. M_H is calculated with Equation 3.

$$H_i = \sum [(P_{wf} - P_e) * \Delta t] \quad \text{Equation 1}$$

$$W_i = \sum (Q_w * \Delta t) \quad \text{Equation 2}$$

$$m_H = \Delta H_i / \Delta(\ln(W_i)) \quad \text{Equation 3}$$

Discussion

When using the Hall Plot, there are several requirements and assumptions that must be met. The bottomhole pressure must be directly measured or calculated from surface pressures (accounting for hydrostatic pressure and friction loss). The bottomhole pressure and the reservoir pressure must be converted to the same reference depth. The bottomhole pressure must be greater than the static reservoir pressure. The reservoir should exhibit steady state flow, such that the static reservoir pressure does not increase significantly over time (since the pressure generally does increase as a result of injection, the Hall Plot generally curves slightly upward). The well cannot be deviated in the injection interval. Lastly, null data must be accounted for, as these will create significant issues in the calculations.

As stated before, the Hall Plot indicates relative changes in the injectivity of the well, rather than calculating the actual injectivity index. Assuming there are no changes to the operation conditions (for example the injection rate) and the reservoir conditions (for example permeability and skin), the Hall Plot and the derivative should theoretically form straight, near-overlapping lines. The Hall Integral continuously increases, but the derivative can fluctuate up and down. Kinks in this derivative line occur when sudden changes to the injection condition occur. Common causes include changes to the injection rate, well stimulation, and fracturing. Bending of the derivative occurs when gradual changes occur, like reservoir damage. Bending upward of the derivative generally indicates reservoir damage, but kinks downward generally indicate fracturing. These kinks and bends generally cause separation of the Hall Integral and the derivative plots. However, it is important to note that while the Hall Plot can indicate fracturing, it does not provide details about what caused the fracturing. Instead, well tests like step rate tests or falloff tests should be used to identify the details around fracture (like formation parting pressure or fracture length).

Recommendations

The Hall Plot is particularly attractive to well owners and operators because it does not cause interruptions to the well operations. It only requires constant injection volumes and bottomhole pressure data to produce well injectivity data. Through analyzing the derivative of the Hall Integral, formation damage and fracturing can be indicated. However, to quantify the data (skin, permeability, formation parting pressure, and fracture length) surrounding the formation damage or fracturing, well tests like falloff tests and step rate tests are required.

References

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